# QUIET-TIME PROPERTIES OF LOW-ENERGY (<10 MeV PER NUCLEON) INTERPLANETARY IONS DURING SOLAR MAXIMUM AND SOLAR MINIMUM

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## ABSTRACT

We have examined the abundances and spectra of $\sim$1–10 MeV per nucleon protons, $^3$He, $^4$He, C, O, and Fe during solar quiet periods from 1978 to 1987 in an effort to investigate the recent suggestion by Wenzel et al. that the ions may be of solar origin. We find that the intensities of the ions, other than O, fall by an order of magnitude between solar maximum and solar minimum, and that the >1 MeV per nucleon ions exhibit weak streaming away from the Sun. More significantly, the quiet-time ions during solar maximum have $^3$He-rich and Fe-rich abundances which are established characteristics of small impulsive solar flares. Thus, we suggest that small unresolved impulsive flares make a substantial contribution to the "quiet-time" fluxes. $^4$He from these flares may also contribute strongly to the ion spectra that were reported for the 35–1600 keV energy range by Wenzel et al.

Subject headings: cosmic rays: abundances — interplanetary medium — particle acceleration — Sun: particle emission

## I. INTRODUCTION

Low-energy ($\leq$10 MeV per nucleon) ions in interplanetary space during quiet times, when particles associated with solar events, interplanetary shocks, corotating particle events, or of magnetospheric origin are not obviously present, have been investigated principally using mid-1960s and mid-1970s solar minima data (Fan et al. 1970; Lin et al. 1973; Krimigis et al. 1977; Zamow 1975; Mason, Gloeckler, and Hovestadt 1979 and references therein). A major emphasis of these studies was to establish whether an upturn in the cosmic-ray spectrum at $\leq$10 MeV per nucleon was of Galactic origin or was due to a solar, interplanetary, or magnetospheric source.

Recently Wenzel et al. (1990) used data from the EPAS instrument on the ISEE 3/ICE spacecraft to study low-energy (35–1600 keV) quiet-time ions (assumed to be protons) during solar maximum conditions in 1978–1981. They suggested that these ions were solar in origin. Here we use complementary ISEE 3/ICE observations from 1978 to 1987 to investigate the spectra, abundances, and anisotropy of 1–10 MeV per nucleon ions during solar maximum and solar minimum quiet-time intervals in an effort to determine the origin of the particles.

## II. INSTRUMENTATION

The ISEE 3/ICE Medium Energy Cosmic Ray Experiment (von Rosenvinge et al. 1978) measures the spectrum and composition of $\geq$1 MeV per nucleon ions using a two-parameter method with very low instrumental background. Also, the 1–4 MeV per nucleon ion counts in a viewing cone within 25° of the ecliptic plane are accumulated in eight azimuthal sectors, allowing investigation of the ion anisotropy. Following launch on 1978 August 12, ISEE 3/ICE orbited around the Sun-Earth L1 libration point, $1.5 \times 10^6$ km upstream of Earth, from 1978 November until 1982 September. From 1982 October until 1983 December, it was largely in the geomagnetic tail. Then after 1983 December, it was placed in a heliocentric orbit and

advanced ahead of Earth by $\sim$0.2 AU yr$^{-1}$. By 1987, the data coverage was very restricted, so we only consider observations made up to this time.

## III. SELECTION OF QUIET-TIME INTERVALS

The quiet-time periods selected are intervals in the solar wind between launch and early 1987 with low ion fluxes, specifically a 1–4 MeV per nucleon ion flux of $<10^{-2}$ (cm$^2$ sr s MeV per nucleon), which extend at least 1 day and do not include solar high-energy ion and electron enhancements. Figure 1 shows examples of quiet-time periods during 1979, near solar maximum (top panel) and in 1986, near solar minimum (bottom panel). Solar maximum quiet periods occur between large particle events, whereas at solar minimum, quiet conditions are maintained for longer intervals. The chosen periods agree well with those identified independently by Wenzel et al. (1990).

## IV. QUIET-TIME ION SPECTRA AND COMPOSITION

The energy spectrum and composition of quiet-time <10 MeV per nucleon ions are examined by summing Medium Energy Cosmic Ray Experiment ion fluxes separately over solar maximum and solar minimum quiet-time intervals. Solar maximum observations include 57 days between launch and 1984 April (when solar activity [e.g. indicated by sunspot number (Solar Geophysical Data)] declined to low levels). Solar minimum observations were made on 257 days after this time up to 1987 January.

Solar maximum and solar minimum differential energy spectra for various 1–10 MeV per nucleon ions are shown in Figures 2a and 2b. The spectra can generally be fitted by power laws in energy, $dJ/dE \sim E^\gamma$, with $\gamma \sim -2.5$ (see Table 1). The proton, $^3$He, $^4$He, Fe, and C ion fluxes decrease from solar maximum to solar minimum (no Fe and C were detected at solar minimum). In particular, the proton and $^4$He intensities

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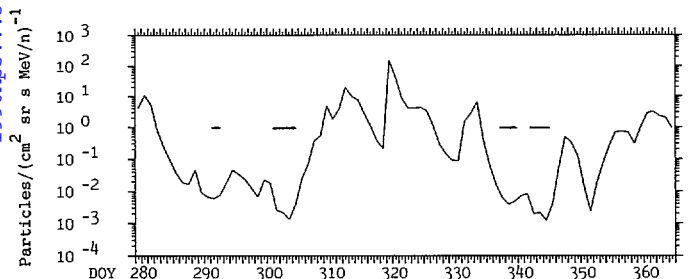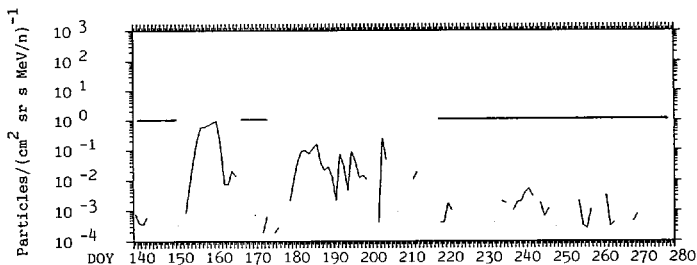


FIG. 1.—Examples of quiet-time intervals (1–4 MeV per nucleon ion flux $< 10^{-2}$ [cm² sr s MeV per nucleon]) near solar maximum (*top panel*) and near solar minimum (*bottom panel*). The data are averaged over 1 day intervals.

TABLE 1

QUIET-TIME SPECTRA FOR 1–10 MeV PER NUCLEON IONS: $dJ/dE \sim E^\gamma$

| Species | $\gamma$(1978 Aug–1984 Apr) | $\gamma$(1984 Oct–1987 Jan) |
|---|---|---|
| Proton ......... | $-2.5$ | $-3.1$ |
| ³He ............ | $-3.1$ | $-2.3$ |
| ⁴He ............ | $-3.0$ | $-2.6$ |
| C .............. | [a] | ... |
| O .............. | $-1.6$ | $-0.3$ |
| Fe ............. | $-3.5$ | ... |

[a] One count per channel, $\gamma$ not determined.

anomalous oxygen fluxes reported by Mewaldt (1990) suggests that anomalous oxygen dominates the quiet-time oxygen population. The solar maximum quiet-time Fe/O ratio is approximately 1, indicating that the quiet-time composition is extremely Fe-rich (Reames 1990). The implications of the ³He and Fe-rich solar maximum composition will be discussed below.

In Figure 3 we compare the solar maximum ~4–20 MeV proton and ⁴He ion spectra with the EPAS 35–1600 keV ion spectrum (after Wenzel *et al.* 1990 but averaged over their 4 years of observations and corrected for a small instrumental background), all plotted in terms of total kinetic energy rather than kinetic energy per nucleon. The EPAS spectrum, when extrapolated to higher energies, appears to lie above the MeV proton spectrum. However, EPAS cannot distinguish ions with the same total kinetic energy, so it is possible that ions heavier than protons may contribute to the EPAS flux. In support of this suggestion, we note that, at least at ~10 MeV total kinetic energy, the proton and ⁴He fluxes are similar. Thus if protons and ⁴He have similar spectral shapes at lower energies, then ⁴He ions may significantly contribute to the EPAS ion spectrum.

fall by a factor of ~5, while the ³He flux shows a more dramatic fall, by a factor of >20. This causes the ³He/⁴He ratio to decrease from ~70% at solar maximum to ≤10% (the instrumental background) at solar minimum, indicating that ³He ions virtually disappeared at solar minimum. The high solar maximum ³He/⁴He ratio (compared to a coronal value of $5 \times 10^{-4}$) implies that these ions are "³He-rich" (Reames 1990).

The oxygen spectrum is much harder, in particular at solar minimum when the >3 MeV per nucleon O fluxes actually increase from solar maximum values. The similarity with

## V. QUIET-TIME ION ANISOTROPY

The anisotropy may also provide information on the origin of quiet-time >1 MeV per nucleon ions, though our anisotropy observations are limited by a duty cycle of only ~1.7% at solar maximum and ~0.5% at solar minimum. Summing
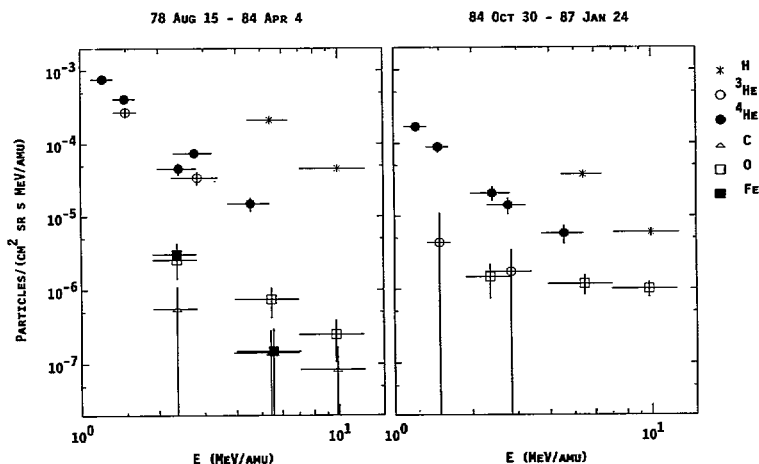


FIG. 2.—Quiet-time ion spectra for (a) "solar maximum" (1978 August–1984 April) and (b) "solar minimum" (1984 October–1987 January), showing the large ³He/⁴He and Fe/O abundance ratios at solar maximum which indicate a contribution from small impulsive solar flares.
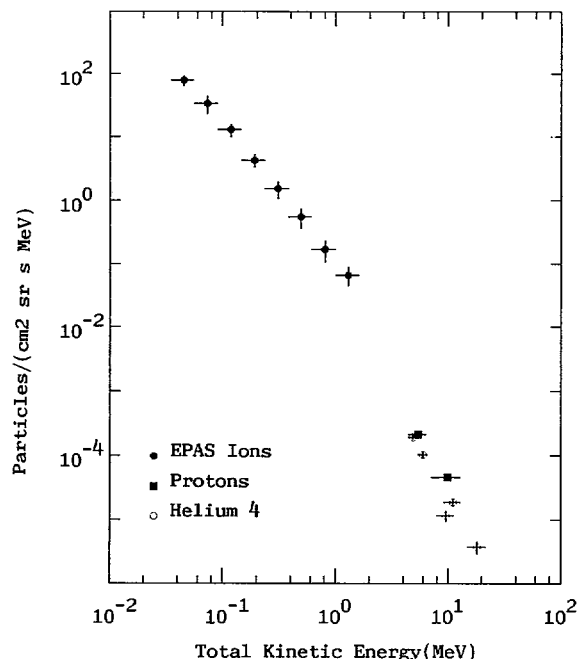
FIG. 3.—Comparison of solar maximum 35–1600 keV ion spectrum (after Wenzel *et al.* 1990) with ≤20 MeV proton and ⁴He spectra plotted in terms of total kinetic energy. While the low-energy and MeV ion spectra are reasonably consistent, the similar MeV proton and ⁴He fluxes suggest that ⁴He may be a significant contributor to the lower energy spectrum in addition to protons.



a) 78 Aug 15 – 84 Apr 4



b) 84 Oct 30 – 87 Jan 24

FIG. 4.—Azimuthal >1 MeV per nucleon quiet-time ion flux and magnetic field angle distributions for (*a*) solar maximum and (*b*) solar minimum periods in the spacecraft frame. The ions show only weak streaming, largely accounted for by convection with the solar wind, while the magnetic field is most frequently along the Parker spiral direction.
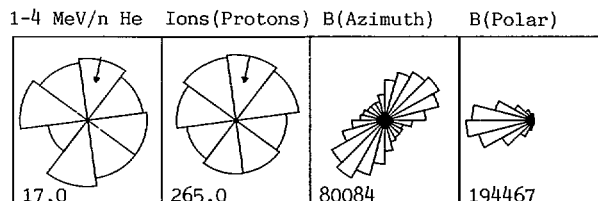
over all the solar maximum intervals gives the azimuthal intensity distribution in Figure 4*a*. The sun lies to the top of this figure. Ion fluxes are plotted versus sector viewing directions for 1–4 MeV per nucleon He (first panel) and ions (principally protons, second panel). The number of ions detected in the maximum count sector is given below each plot. The third and fourth panels show the magnetic field azimuthal and polar angle frequency distributions which indicate that the field lay generally along the nominal Parker spiral direction.

In the spacecraft frame, the solar maximum 1–4 MeV per nucleon ion distribution shows a slight antisolar streaming. This is consistent with an isotropic population in the solar wind frame convecting past the spacecraft since the first Fourier harmonic ($A_0$) of the distribution, representing the ion streaming, has a magnitude of 14% ± 3% and lies parallel to the solar wind velocity, and compares with a magnitude of ∼17% expected from an isotropic ∼1.5 MeV per nucleon ion distribution convecting at ∼400 km s⁻¹. The 1–4 MeV per nucleon He distribution is less easily interpreted. However, the variation in the number of particles in each sector is within limits for a near-isotropic distribution.
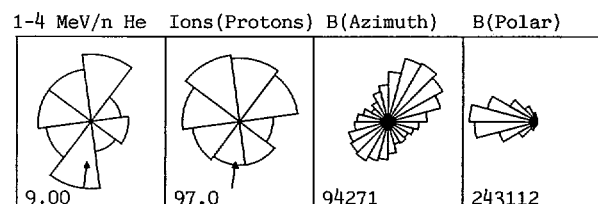
During solar minimum (Fig. 4*b*), there is an excess of ions streaming from east of the Sun, corresponding in the solar wind frame to a slight flow approximately perpendicular to the average field direction ($A_0 = 12\%$ at 228°). The He anisotropy is again dominated by statistical fluctuations.

### VI. SUMMARY AND DISCUSSION

*ISEE 3/ICE* observations of <10 MeV per nucleon quiet-time ions in 1978–1987 indicate that proton, ³He, ⁴He, C, and Fe (but not O) fluxes are correlated with solar activity. The differential energy spectra approximate to power laws in energy with $\gamma \sim -2.3$ to $-3.5$, similar to those obtained for

protons and He during the last three solar cycles as summarized in Table 2.

The correlation with solar activity rules out a Galactic source for ≤10 MeV per nucleon quiet-time ions and favors a solar origin. Since the ions are not obviously associated with individual solar events, they may be remnants of large solar particle or shock-associated events, or they may be accelerated in small solar flares. Since small impulsive solar flares produce ³He-rich (³He/⁴He ∼ 0.1–10) and Fe-rich (Fe/O ∼ 1) interplanetary particle enhancements (Reames 1990), the ³He and Fe-rich solar maximum quiet-time ion composition suggests that small solar flares must contribute to this population. These ions are not simply remnants of large solar particle or shock-associated events, which tend to have much lower ³He/⁴He (<0.1) and Fe/O (∼0.1) ratios (Cane, Reames, and von Rosenvinge 1990). (In support of this conclusion, the ³He/⁴He ratio increases [to ∼86%] if a lower "quiet-time" threshold [5 × 10⁻³ (cm² sr s MeV per nucleon)] is chosen, presumably due to the further exclusion of late decay phases of large solar particle events from the analysis.) The disap-

TABLE 2

QUIET-TIME SPECTRA FOR <10 MeV PER NUCLEON IONS: $dJ/dE \sim E^\gamma$

| Source | $\gamma$(Proton) | $\gamma$(He) | Year(s) |
|---|---|---|---|
| This work ........................ | −2.5 | −3.0 | 1978–1984 |
| This work ........................ | −3.1 | −2.6 | 1984–1987 |
| Wenzel *et al.* 1990 ............... | −2.4 ± 0.1 | ... | 1978–1981 |
| Mason *et al.* 1979 ................ | −3.2, −4 | −2.6 | 1977 |
| Krimigis *et al.* 1977 ............. | −2.3 ± 0.3 | ... | 1975 |
| Gloeckler *et al.* 1975 ........... | −1.8 | ... | 1974 |
| Krimigis *et al.* 1975 ............. | −3.1 ± 0.2 | ... | 1973 |
| Mewaldt *et al.* 1975 ............. | −4 | −3.6 | 1972–1973 |
| Zamow 1975 ..................... | −(2.2–3.3) | −(1.9–3.2) | 1964–1972 |
| Simpson and Tuzzolino 1973 ... | −3.0 ± 0.3 | −3.0 ± 0.3 | 1972–1973 |
| Fan *et al.* 1970 .................... | −1.6 | −2.1 | 1964–1967 |
| Fan *et al.* 1968 .................... | −2.4 | −2.4 | 1964–1965 |

pearance of $^3$He and Fe at solar minimum may then be due to a fall in the number of small flares, associated with decreased solar activity.

Protons and $^4$He are still present at solar minimum however, so other sources do contribute to the quiet-time ion population. Unfortunately, the near-isotropy of the solar wind frame ion distribution provides little clear evidence of the origin of these ions. For example, they may be emitted from the Sun and subsequently scattered back from magnetic field irregularities in the outer heliosphere, eventually forming a low-level, well-scattered essentially isotropic distribution. They could also be accelerated in the outer heliosphere at corotating interaction regions (Pesses *et al.* 1979) and again may eventually be scattered into near-isotropy in the solar wind frame. However, these ions typically have Fe/O ratios of $\sim 0.1$ (Gloeckler *et al.* 1979) and so could not account for the Fe-rich quiet-time ions. We do not consider a magnetospheric source of quiet-time ions to be a serious possibility since the ions do not stream away from Earth, and $^3$He ions are unlikely to be of terrestrial origin. Also during the solar minimum periods considered here, *ISEE 3/ICE* was not in the vicinity of Earth.

In summary, solar particles apparently contribute to fluxes of $\leq 10$ MeV per nucleon quiet-time protons, $^3$He, $^4$He, C, and Fe, based on their solar cycle modulation (which rules out a significant Galactic component) and composition. The large $^3$He/$^4$He ratio and Fe abundance suggest that quiet-time ions are not simply remnants of large particle events but include a significant contribution from small solar flares. The nearly isotropic distribution indicates that the ions have undergone significant scattering in the solar wind and are not emitted in a continuous "drizzle" from the Sun. Corotating ions may also contribute to the quiet-time fluxes. A magnetospheric source is unlikely. Finally, the quiet-time $\geq 5$ MeV per nucleon O fluxes are dominated by the anomalous cosmic-ray component, especially at solar minimum.

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